10/586076

IAP11 Rec'd PCT/PTO 14 JUL 2006

[10191/4844]

METHOD AND COMPUTER PROGRAM FOR GENERATING A MODEL FOR THE RESPONSE OF A CONTROL DEVICE

The present invention relates to a method for generating a model for the functional response of a control device, the control device being designed for calculating a suitable manipulated variable for a controlled system, in particular an air path system of an internal combustion engine, in response to a preselected setpoint value for a controlled variable of the controlled system. In addition, the present invention relates to a control system and a regulating system, each having a control device designed in this way. Finally, the present invention also relates to a data medium having the aforementioned computer program.

Background Information

Such a method and such systems are essentially known from the related art, in particular WO 89/09953. This describes a method for tracking the trajectory of axial positions of a robot. It is assumed here that the controlled system is linear and may be described with the help of a transfer function G(s) in the frequency range. A manipulated variable for the controlled system is determined from the trajectory sequence, i.e., the preselected setpoint characteristic of the axial motion, with the help of a control device whose transfer function corresponds to the inverse transfer function of the controlled system. To be able to set the controlled variable even more precisely at the predetermined setpoint characteristic, the manipulated variable is corrected, if necessary, with the help of a regulating device connected in parallel with the control device. To this end, the regulating device receives as a controlled variable a control deviation between a setpoint position and an actual axial position. The

regulating device calculates from this control deviation a correction factor for the manipulated variable, this correction factor being applied to the manipulated variable calculated by the control device to then provide the controlled system with a corrected manipulated variable generated in this way.

The method described in WO 89/09953 has the disadvantage that it is applicable only to controlled systems having a linear response and having only a single controlled variable.

Against the background of this related art, the object of the present invention is therefore to provide a method and a computer program for generating a model for the functional response of a control device as well as a control system and a regulating system, each having a control device having a model generated in this way and a data medium having the aforementioned computer program, which allow such a model to be generated for a control device even when the response of a controlled system downstream from the control device is not linear and multiple controlled variables are to be controlled and/or regulated.

This object is achieved by the method as recited in Patent Claim 1. This method is characterized in that inversion of the model for the controlled system for generating the model for the control device includes the following steps: calculating an equation for the N^{th} derivation of the controlled variable as a function of the manipulated variable and the controlled variable itself and/or its derivatives of the n^{th} order with respect to time, where $n = 1, \ldots, N-1$; and generating the model for the control device by solving the equation for the N^{th} derivatives of the controlled variable for the manipulated variable.

Advantages of the Invention

This method according to the present invention offers the advantage that it is possible with this method to generate a model for a control device within a control system or a regulating system even when the particular controlled system in these systems has a nonlinear response and/or multiple controlled variables are to be controlled or regulated. In any case, however, the prerequisite is that the controlled system must be describable in the form of a mathematical model using physically motivated equations. The model generated according to the present invention for the control device is then valid in the entire range of operation of the controlled system mapped by the model.

In application of the method according to the present invention, it is advantageously not usually necessary for the model for the controlled system to describe its functional response to the full extent and in great detail. Instead, for the present invention it is sufficient to use a model of the controlled system that has possibly been reduced and maps its dynamics and linear and/or nonlinear response only inasmuch as this is relevant for the regulating operation.

An exemplary embodiment of the generation of a model for the control device according to the present invention is the subject matter of a subclaim.

The object defined above is also achieved by a computer program for performing the method, by a data medium having this computer program and by a control system and a regulating system, each having a control device having the model generated according to the present invention. The advantages of these approaches correspond to the advantages mentioned above with respect to the method claimed.

In addition, a regulating device provided in the regulating system advantageously results in an additional precisation, i.e., correction of the manipulated variable, so that with the help of this regulating device, the controlled variable may be adjusted even more precisely to the particular predetermined setpoint value. When using a control device having the model generated according to the present invention, this regulating device need only correct minor deviations in the controlled variable from the setpoint value and/or a predetermined setpoint trajectory; it is therefore not excessively burdened in particular in comparison with known regulating devices based on engine characteristics maps, and therefore this device is very robust.

Since the model is valid in the entire operating range of the controlled system - at least as a rule - only the particular regulator parameters need be adjusted once for the entire operating range of the controlled system in the case of the regulating device. When using the model generated according to the present invention for the control device, it is not necessary to constantly adapt the regulator parameters to the ever-changing operating points of the controlled system.

Drawing

The description is accompanied by a total of three figures.

Figure 1 shows a control system according to the present invention;

Figure 2 shows the method according to the present invention; and

Figure 3 shows a regulating system according to the present invention.

Description of the Exemplary Embodiments

The present invention is explained in greater detail below in the form of exemplary embodiments with reference to the figures cited above.

Figure 1 shows a control system 100 for controlling a controlled variable y. This control system 100 includes a setpoint value preselecting device 110 for preselecting at least one setpoint value y_d for controlled variable y, in particular in the form of a trajectory sequence. In the example illustrated in Figure 1, setpoint value preselecting device 110 generates n + 1 setpoint values in the form of a setpoint value y_d and its first through n^{th} derivatives with respect to time.

In addition, control system 100 includes a control device 120 for converting these setpoint values into at least one manipulated variable u_d. Manipulated variable u_d is used as an input variable for a controlled system 130 for controlling controlled variable y at the output of the controlled system.

Manipulated variable u_d is to be dimensioned by control device 120 so that controlled variable y at the output of controlled system 130 is set at setpoint value y_d output by setpoint value preselecting device 110. To do so, it is necessary for control device 120 to be designed suitably. This suitable design of control device 120 is the subject matter of the present invention and is described in detail below.

Figure 2 shows the individual method steps for generating a suitable mathematical model for describing the functional response of control device 120 in detail. It is assumed here that a mathematical model in the form of physical model equations is known for controlled system 130. These model equations for controlled system 130 preferably include only the dynamic effects that are critical for the regulating operation. As a rule, the model equations are obtained from

conservation laws, i.e., axioms, and are typically representable in the following form:

$$\dot{x} = f(x,u),\ x(0) = x_0 \in \Re^n,\ u \in \Re^m \qquad (1)$$

where

- x represents a state vector, preferably including only the state variables required from a regulating standpoint;
- u represents a manipulated vector which includes at least one manipulated variable;
- f represents any mathematical function, in particular a differential equation;
- $x_i(0)$ represents a state variable at point in time $t = 0$; and
- x_0 represents an initial value.

All state variables x_i as factors of the state vector as well as all manipulated variables u are essentially time-dependent variables.

The method according to the present invention for calculating a mathematical model for control device 120 is to be explained in greater detail below on the example of the control and/or regulation of a controlled system 130 having nonlinear response. This system may be, for example, a mass moved by an electric motor. The response of this regulated system may be represented by the following nonlinear differential equation system:

$$\dot{x}_1 = \dot{x}_2 \qquad (2a)$$

$$\dot{x}_2 = -x_1^2 - x_2 + x_3 \qquad (2b)$$

$$\dot{x}_3 = -ax_3 - x_2 + u_d \qquad (2c)$$

In this differential system, a state vector x having three state variables x_1, x_2 and x_3 is used to describe the functional response of the controlled system. Due to the use of three state variables, the controlled system may also be called a third-order system. For the aforementioned controlled system, state variable x_1 represents the distance traveled by the mass, state variable x_2 represents the velocity of the mass and state variable x_3 represents the current in the electric motor. Parameter a in equation (2c) is a model parameter. This controlled system also includes a nonlinear spring described by the quadratic term in equation (2b). All states x_i, where $i = 1, \ldots, N = 3$, as well as parameter a and manipulated variable u are standardized and therefore dimensionless.

The method according to the present invention is explained in greater detail below on the example of the calculation of a model for a control device which is adapted to a controlled system having the functional response described in equations (2a)-(2c).

First, as shown in Figure 2, state variable x_i to be regulated is selected from the factors of state vector x. For example, state variable x_1, i.e., the distance traveled by the mass, is selected here as controlled variable y. This choice is described mathematically by the following simple equation (3):

$$y = x_1 \qquad (3)$$

In the following, the method according to the present invention as shown in Figure 2 provides for the first N derivatives $\left(\dot{y}, \ddot{y}, \ldots, \overset{(N)}{y}\right)$ of controlled variable y to be formed.

Thus the first, second, and third derivatives are formed in the concrete example mentioned above having a controlled system of the third order, N = 3. These are calculated taking

account differential equations (2a), (2b) and (2c) of the model of controlled system 130 as follows:

$$y = x_1 \tag{3}$$

$$\dot{y} = \dot{x}_1 = x_2 \tag{4}$$

$$\ddot{y} = \dot{x}_2 = -x_1^2 - x_2 + x_3 \tag{5}$$

$$\dddot{y} = \ddot{x}_2 = -2x_1\dot{x}_1 - \dot{x}_2 + \dot{x}_3$$

$$= -2x_1x_2 - (-x_1^2 - x_2 + x_3) + (-ax_3 - x_2 + u_d)$$

$$= x_1^2 - 2x_1x_2 + (1-a)x_3 + u_d \tag{6}$$

Equations (3), (4) and (5) represent an equation system having three equations and three state variables x_1, x_2 and x_3. In the method according to the present invention, this equation system is used to calculate state vector $x = [x_1, x_2, x_3]^T$. Individual state variables x_i, where i = 1-3, as factors of this state vector are calculated by solving this equation system. For the example here, state vector x is calculated by the procedure described here as follows:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} y \\ \dot{y} \\ y^2 + \dot{y} + \ddot{y} \end{bmatrix} \tag{7}$$

Individual state variables x_i in the representation according to equation (7) are advantageously represented as a mathematical function of only controlled variable y and/or its derivatives with respect to time $\left(\dot{y}, \ddot{y}, \ldots, \overset{(N)}{y}\right)$.

In general, the method according to the present invention then provides for any state variables x_i that might be present in the N^{th} derivative $\overset{(N)}{y}$ of controlled variable y to be replaced by their equivalent representations as a function of

controlled variable y or their derivatives with respect to time according to equation (7).

When applying this procedure to the example, a corresponding replacement must also be made in the N = 3rd derivative of the controlled variable according to equation (6). Equation (6) is then rewritten as follows, taking into account equation (7):

$$\dddot{y} = u_d - \dot{y} - 2y\dot{y} - \ddot{y} - a(y^2 + \dot{y} + \ddot{y}) \qquad (8)$$

Solving equation (8) for manipulated variable u results directly in the model being sought for control device 120 when controlled system 130 to be controlled exhibits the functional response described by equations (2a), (2b) and (2c). The mathematical model for control device 120 then describes manipulated variable u as the output variable of control device 120 in functional dependence on its input variables, i.e., the predetermined setpoint values for controlled variable y. The model for the control device may then be represented as follows for the controlled system mentioned as an example:

$$u_d = \dot{y} + \ddot{y} + \dddot{y} + 2\dot{y}y + a(\dot{y} + \ddot{y} + y^2) \qquad (9)$$

As a model of the control device, equation (9) represents an inversion of the model of controlled system 130 in the form $u_d = f(y)$, which is typically represented in the form $y = g(u_d)$; see equations (3) through (6).

The controlled system described here by equations (2a), (2b) and (2c) as an example in the form of a mass moved by an electric motor merely illustrates the method according to the present invention. Essentially the method according to the present invention may be applied to any type of controlled systems whose functional response is describable by physically motivated model equations, including nonlinear equations. This

is also true in particular of an air path system of an internal combustion engine as a controlled system. Additionally or alternatively to the air path system, in particular by regulating the charging pressure, exhaust gas recycling and filling as well as lambda regulation, any other function in the area of engine management may also be selected as the controlled system. This would include, for example, the injection system, in particular with rail pressure regulation, pressure wave compensation, cylinder pressure regulation and combustion start regulation, engine speed regulation with idling regulation in particular, bucking and load impact attenuation or torque regulation. When using the air path system as the controlled system, such a controlled system may be simulated by suitably selected model equations using the state variables of intake manifold pressure, air mass in the intake manifold, and air temperature in the intake manifold. The method according to the present invention for calculating a suitable model for a control device is also applicable in particular for a model of such a controlled system.

Additional and/or more extensive stabilization of the controlled system from the standpoint of the predetermined setpoint value and/or the predetermined trajectory sequence is implementable by a regulating device 150 connected in parallel with control device 120, as illustrated in Figure 3. The regulating system illustrated in Figure 3 is based on the control system illustrated in Figure 1, where the functional response of control device 120 is described by a mathematical model which has been generated preferably according to the present invention. In addition to control system 100, the regulating system according to Figure 3, however, additionally includes this regulating device 150. This may be any regulator, e.g., a $PIDT_1$ regulator. A control deviation e between controlled variable y at the output of controlled

system 130 and predetermined setpoint value y_d for the controlled variable are sent as input variables to this regulator. Mathematically, control deviation e is calculated as follows:

$$e(t) = y_d(t) - y(t) \qquad (10)$$

Regulating device 150 then generates suitable correction factors for manipulated variable u in accordance with control deviation e, taking into account its regulator parameters K_P, K_I, K_D and/or T_1. A proportional correction factor u_P for manipulated variable u is calculated as follows:

$$u_P = K_P e \qquad (11)$$

where

K_P represents the regulator parameter for the proportional correction factor.

An integral regulator factor u_I is typically calculated as follows:

$$u_I = K_I \int_{t_0}^{t} e(\tau)d\tau \,, \quad u_I(0) = u_I^0 \qquad (12)$$

where

K_I represents the regulator parameter for the integral correction factor; and

u_I^0 represents an initial value for the integral regulating factor.

If regulating device 150 additionally includes a differential regulating factor, it is typically calculated as follows:

$$T_1 \dot{u}_D + u_D = K_D \dot{e} \,, \qquad u_D(0) = u_D^0 \qquad (13)$$

where

K_D represents the regulator parameter for the differential regulating factor; and

u_D^0 represents an initial value for the differential regulating factor.

If regulating device 150 actually includes both a proportional factor as well as an integral and differential factor, then correction factor u_{ctrl} for manipulated variable u is calculated as the sum of these factors as follows:

$$u_{ctrl} = u_P + u_I + u_D \qquad (14)$$

where

u_P represents the proportional regulating factor;

u_I represents the integral regulating factor; and

u_D represents the differential regulating factor.

Total correction factor u_{ctrl} of manipulated variable u calculated in this way is then added with the help of an addition or subtraction device 140 to manipulated variable u_d calculated by control device 120 to finally obtain a resulting corrected manipulated variable u from this addition. The corrected manipulated variable causes an even more precise adjustment of controlled variable y to setpoint quantity y_D in contrast with the manipulated variable supplied by control device 120.

The method according to the present invention is preferably implemented in the form of a computer program. The computer program may, if necessary, be saved together with other computer programs on a computer-readable data medium. The data medium may be a diskette, a compact disk, a flash memory or the like. The computer program saved on the data medium may then be transferred or sold as a product to a customer. As an

alternative to transfer via data media, transfer of the computer program over an electronic communications network, in particular the Internet, is also possible.